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Jet Formation Mechanism of the Gamma-Ray-emitting Narrow-line Seyfert 1 Galaxies

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Abstract

We use a large sample of gamma-ray narrow-line Seyfert 1 galaxies (γ-NLS1s) to study the jet formation mechanisms. We find that the jet power of γ-NLS1s is lower than the maximum jet power of the Blandford–Payne (BP) mechanism. At the same time, we find that there is a significant correlation between jet power and accretion disk luminosity. Moreover, the contribution rates of the accretion to the jet power are larger than that of black hole mass to jet power. These results further suggest that the jet of γ NLS1s is mainly produced by the BP mechanism.

Key words: galaxies: active – galaxies: jets – galaxies: Seyfert

1. Introduction

Narrow-line Seyfert 1 galaxies (NLS1s) are a special class of active galactic nuclei (AGNs) identified by Osterbrock & Pogge (1985), which show narrow Balmer lines (FWHM (Hβ) < 2000 km s^{-1}), weak [O III], strong Fe II emission lines and steep soft X-ray spectra (e.g., Boller et al. 1996; Wang et al. 1996; Leighly 1999). NLS1s are generally regarded as radio-quiet (e.g., Ulvestad et al. 1995; Moran 2000; Boroson 2002). Therefore, discovering the radio-loud narrow-line Seyfert 1 galaxies (RLNLS1s) seems entirely unexpected. In particular, these RLNLS1s were detected by Fermi-Large Area Telescope (Fermi-LAT), which further confirms that they have strong relativistic jets (Abdo et al. 2009). Many authors restudied the properties of these γ-NLS1s. Some authors found that γ-NLS1s have similar properties to flat spectra radio quasars (FSRQs) (e.g., Berton et al. 2019; Paliya et al. 2019). Chen et al. (2021) found that the γ-NLS1s belong to the Fermi blazars sequence. However, it is not clear what is the jet formation mechanism of these γ-NLS1s?

Jet formation has always been a hot topic in astrophysics. At present, there are two most popular jet formation mechanisms. The first is the Blandford–Znajek (BZ) mechanism (Blandford & Znajek 1977): the jets extract rotational energy from a rotating black hole. The jet power mainly depends on the black hole mass. The second is the Blandford–Payne (BP) mechanism (Blandford & Payne 1982): the jets extract rotational energy from the accretion disk. The power extracted in this way is proportional to the disks magnetic field. If the squared magnetic field is proportional to the accretion rate, then there will be a correlation between jet power and accretion disk luminosity (Ghisellini et al. 2014). Many authors have found that jet and accretion are closely related (e.g., Rawlings & Saunders 1991; Celotti et al. 1997; Cao & Jiang 1999; Ghisellini et al. 2014; Chen et al. 2015). Livio et al. (1999) suggested that the BP mechanism dominates over the BZ mechanism. However, some authors put forward the opposite view. Chai et al. (2012) found that the BZ mechanism may dominate over the BP mechanism for blazars.

In this paper, we investigate the jet formation in γ-NLS1s. The cosmological parameters $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ are adopted in this work. Section 2 presents the samples; Section 3 describes the jet formation mechanisms; Section 4 describes the results and discussions; Section 5 presents the conclusions.

2. The Sample

We try to collect a large sample of γ-NLS1s. We consider the sample of Paliya et al. (2019). Paliya et al. (2019) studied the physical properties of 16 γ-NLS1s. The accretion disk luminosity, X-ray luminosity in 0.3–10 keV, and black hole mass come from their work. The accretion disk luminosity and black hole mass are obtained by using the SED modeling (see Paliya et al. 2019). Conventionally, optical spectral line and continuum measurements are used to derive them (see Shaw et al. 2012). It is found that parameters derived from both methods reasonably agree with each other (e.g., Paliya et al.

Table 1
The Sample of γ-NLS1s

Name (1)	Redshift (2)	$\log(M/M_{\odot})$ (3)	$\log l_{\rm disk}$ (4)	$f_{1.4\ \rm GHz}$ (5)	$\log P_{\rm jet}$ (6)	$\log P_{\rm rad}$ (7)	δ (8)	Γ (9)
1H 0323+342	0.061	7.3	45.3	613.5	44.163	43.94	13.6	8
SBS 0846+513	0.584	7.59	44.43	266.3	44.799	44.96	19.1	11
CGRaBS J0932+5306	0.597	8	45.7	481.6	44.896	44.96	14.7	9
GB6 J0937+5008	0.275	7.56	43.71	166.6	44.461	44.51	15.4	10
PMN J0948+0022	0.585	8.18	45.7	69.5	44.594	46.05	15.7	10
TXS 0955+326	0.531	8.7	46.23	1247.1	44.998	45.01	12.3	7
FBQS J1102+2239	0.453	7.78	44	2.5	43.998	45.52	19	17
CGRaBS J1222+0413	0.966	8.85	46.18	800.3	45.155	46.68	16.5	11
SDSS J124634.65+023809.0	0.362	8.48	44.48	35.7	44.325	44.68	17.8	13
TXS 1419+391	0.49	8.48	45.34	85.7	44.563	44.83	13.6	8
PKS 1502+036	0.407	7.6	44.78	394.8	44.733	45.26	17.2	12
TXS 1518+423	0.484	7.85	44.7	138.4	44.629	44.76	17.8	13
RGB J1644+263	0.145	7.7	44.48	128.4	44.205	43.74	14.7	9
PKS 2004-447	0.24	6.7	43	471	44.57	44.37	17.2	12
TXS 2116-077	0.26	7.2	44	96.1	44.357	44.15	17.2	12
PMN J2118+0013	0.463	7.77	44.94	147.9	44.625	44.66	14.7	9

Note. Column (1) is the name of sources; Column (2) is redshift; Column (3) is the black hole mass; Column (4) is the accretion disk luminosity; Column (5) is the 1.4 GHz radio flux in units mJy; Column (6) is the jet kinetic power estimated from 1.4 GHz radio power; Column (7) is the radiative jet power; Column (8) is the Doppler factors; Column (9) is the bulk Lorentz factors.

2017). The bolometric luminosity of γ-NLS1s includes the radiations from both the accretion disk and the jet (Sun et al. 2015), i.e., $L_{\rm bol} = L_{\rm disk} + L_{\rm jet}^{\rm bol}$. The bolometric luminosity of a jet can be estimated by the following formula (Ghisellini et al. 2014; Paliya et al. 2019),

$$P_{\rm rad} = 2fL_{\rm jet}^{\rm bol}\Gamma^4/\delta^6, \tag{1}$$

where the factor of 2 indicates two jets, $f = 16/5$ for the external Compton (EC). Paliya et al. (2019) suggested that the bolometric output of γ-NLS1s radiates from the X-ray to γ-ray bands dominated by EC. The $P_{\rm rad}$ is radiative jet power. The δ and Γ are Doppler and bulk Lorentz factors, respectively. The radiative jet power, Doppler factor, and bulk Lorentz factors come from the work of Paliya et al. (2019). Thus, we use Equation (1) to get jet bolometric luminosity.

Komossa et al. (2018) used the following formula to estimate the jet kinetic power of RLNLS1s (Bîrzan et al. 2008),

$$\log P_{\rm jet} = 0.35(\pm0.07)\log P_{1.4} + 1.85(\pm0.10), \tag{2}$$

where $P_{\rm jet}$ is in units 10^{42} erg s^{-1}, and $P_{1.4}$ is in units 10^{40} erg s^{-1}. The $P_{1.4}$ is radio luminosity at 1.4 GHz. The radio luminosity is estimated by using the relation $L_\nu = 4\pi d_L^2 S_\nu$, $S_{(\nu)} = S_\nu^{\rm obs}(1+z)^{\alpha-1}$, where α is spectral index, $\alpha = 0$ is adopted (Donato et al. 2001; Abdo et al. 2010; Komossa et al. 2018). Following Komossa et al. (2018), we also use Equation (2) to estimate the jet power. The data are listed in Table 1.

3. Jet Formation Mechanisms

Some authors have calculated the jet power of the BZ and BP mechanisms (e.g., Ghosh & Abramowicz 1997; Livio et al. 1999; Meier 2001; Cao 2003). We use similar methods to derive the maximal jet power of BP and BZ mechanisms.

3.1. The BP Mechanism

The maximal jet power of the BP mechanism is

$$P_{\rm BP}^{\rm max} = 4\pi\int\frac{B_{\rm pd}^2}{4\pi}R^2\Omega(R)dR, \tag{3}$$

where $B_{\rm pd}$ is the strength of the large-scale magnetic field on the disk surface. Livio et al. (1999) have suggested that the large-scale magnetic field can be estimated by the following formula

$$B_{\rm pd} \sim \frac{H}{R}B_{\rm dynamo}. \tag{4}$$

Laor & Netzer (1989) gave the scale height of the disk, H/R,

$$\frac{H}{R} = 15.0\dot{m}r^{-1}c_2, \tag{5}$$

Novikov & Thorne (1973) defined the coefficient c_2, and other parameter are defined by

$$r = \frac{R}{R_G},\ R_G = \frac{GM_{\rm bh}}{c^2},\ \dot{m} = \frac{\dot{M}}{\dot{M_{\rm Edd}}},$$
$$\dot{M_{\rm Edd}} = \frac{L_{\rm Edd}}{\eta_{\rm eff}c^2} = 1.39\times10^{15}{\rm m\ kg\ s^{-1}},\ m = \frac{M_{\rm bh}}{M_{\odot}}. \tag{6}$$

The strength of the dynamo magnetic field is calculated by the following formula (Cao 2003)

$$B_{\rm dynamo} = 3.56 \times 10^8 r^{-3/4} m^{-1/2} A^{-1} B E^{1/2} G, \tag{7}$$

where A, B, and E are defined by Novikov & Thorne (1973). The A, B, and E are estimated by the following formula,

$$\begin{aligned} A &= 1 + a^2 x^{-4} + 2a^2 x^{-6}, \\ B &= 1 + a x^{-3}, \\ E &= 1 + 4a^2 x^{-4} - 4a^2 x^{-6} + 3a^4 x^{-8}, \\ x &= \sqrt{r}. \end{aligned} \tag{8}$$

In standard accretion disk models, the Kepler angular velocity is given by Cao (2003),

$$\Omega(r) = \frac{2.03 \times 10^5}{m(a + r^{3/2})} s^{-1}, \tag{9}$$

where a is the spin of black hole.

Using Equations (3)–(9) the maximal jet power of the BP mechanism can be obtained through integral Equation (3) when some parameters (m, $\dot{m}$, a) are given.

3.2. The BZ Mechanism

The maximal jet power of the BZ mechanism is given by the following formula (e.g., Ghosh & Abramowicz 1997; MacDonald & Thorne 1982),

$$P_{\rm BZ}^{\rm max} = \frac{1}{32} \omega_F^2 B_\perp^2 R_H^2 c a^2, \tag{10}$$

the horizon radius is $R_H = [1 + (1 - a^2)^{1/2}] G M_{\rm bh}/c^2$. In order to estimate the maximum jet power, following the previous work (e.g., MacDonald & Thorne 1982; Livio et al. 1999; Cao 2003), we use $\omega_F = 1/2$, $B_\perp \simeq B_{\rm pd}(R_{\rm ms})$. The $R_{\rm ms}$ is defined by the following formula,

$$\begin{aligned} R_{\rm ms} &= R_G\{3 + Z_2 - [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2}\}, \\ Z_1 &\equiv 1 + (1 - a^2)^{1/3}[(1 + a)^{1/3} + (1 - a)^{1/3}], \\ Z_2 &\equiv (3a^2 + Z_1^2)^{1/2}. \end{aligned} \tag{11}$$

4. Results and Discussion

In Figure 1, we show the relation between $\log P_{\rm jet}/L_{\rm bol}$ and $\log L_{\rm bol}/L_{\rm Edd}$. The jet kinetic power is estimated from the low-frequency radio luminosity by using Equation (2). The maximal jet power of the BP mechanism is calculated by using Equations (3), (4) and (7). Similarly, the maximal jet power of the BZ mechanism is estimated by using Equations (4), (7) and (10). From Figure 1, we find that the jet power of all sources in our sample is lower than the maximum jet power extracted from a magnetized accretion disk (see Figure 1, below the solid line). These results imply that jet power of all sources can be powered by the BP mechanism. At the same time, we also find that the jet power of about 40% of sources with high accretion rates is lower than the maximum jet power extracted from the rapidly rotating black hole (see Figure 1, below dashed lines). These 40% sources with a high accretion rate can be explained by the BZ mechanism.

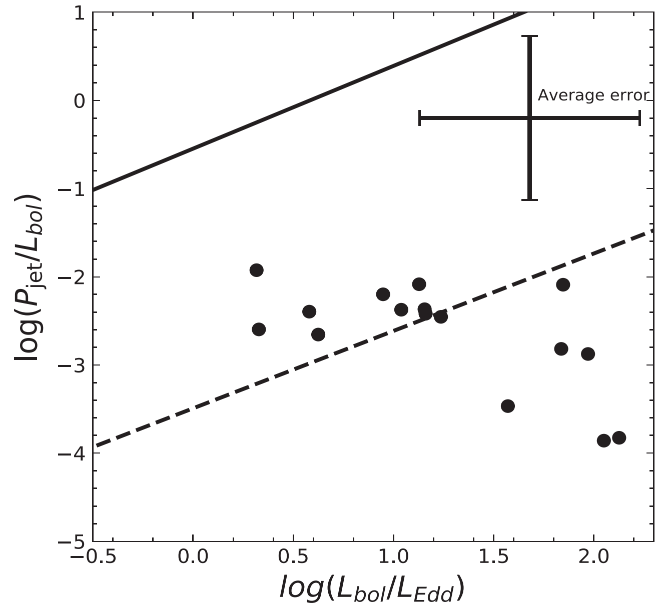

Figure 1. The $L_{\rm bol}/L_{\rm Edd}$ vs. $P_{\rm jet}/L_{\rm bol}$. The solid line is maximal jet power $P_{\rm BP}^{\rm max}$ extracted from a accretion disk. The dashed line is maximal jet power $P_{\rm BZ}^{\rm max}$ extracted from a rapidly spinning black hole $a = 0.99$. The black filled circle is γ-NLS1s.

At low accretion rates, the accretion disks may be truncated by the evaporation and become advection-dominated accretion flows (e.g., Yuan & Narayan 2014). The condensation of corona gas provides fuel for a small inner accretion disk (e.g., Liu et al. 2007). With the increase in accretion rate, the contribution of the inner disk increases. The inner thin disk for γ-NLS1s may extend to around the innermost stable circular orbit (ISCO), and thus their jets may be produced via the BP and/or BZ mechanisms (e.g., Sun et al. 2015). At the same time, an increase in accretion rate may also result in insufficient evaporation to completely remove the disk, then the IC scattering of the soft photons on the disk condenses the corona (e.g., Liu et al. 2007). In this case, a complete thin disk with a weak corona exists. The thin disk also extends around the ISCO, and the jets may be mainly produced by the BZ mechanism.

However, we also note that there are some uncertainties in black hole mass, accretion disk luminosity, jet radiation power and jet kinetic power. The uncertainty of black hole mass is 0.4 dex (Ghisellini & Tavecchio 2015); the uncertainty of 0.3 dex in $\log L_{\rm disk}$ and 0.23 dex in $\log P_{\rm rad}$ (Ghisellini et al. 2014); the uncertainty of jet kinetic power is 0.85 dex (Bîrzan et al. 2008). We calculate the uncertainty in $L_{\rm bol}$ propagating the error associated with $\log L_{\rm disk}$ and $\log P_{\rm rad}$. The uncertainties of a

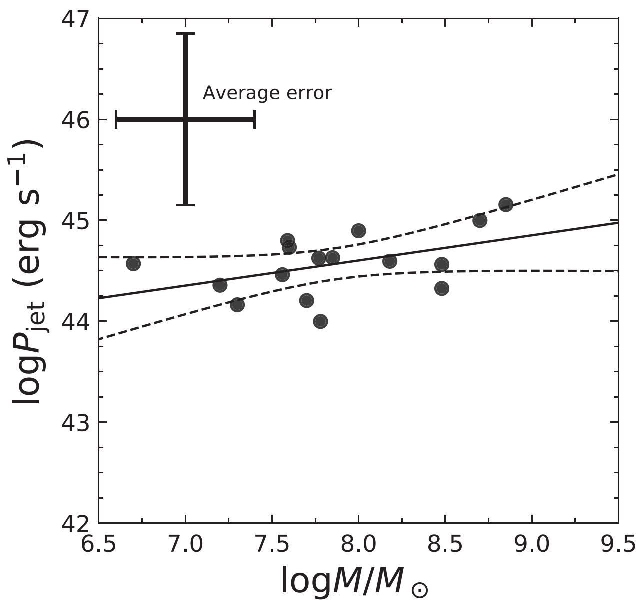

Figure 2. Relation between black hole mass and jet power. The solid lines correspond to the best-fit linear models obtained with the symmetric least-squares fit. The dashed lines indicate 2σ confidence band.

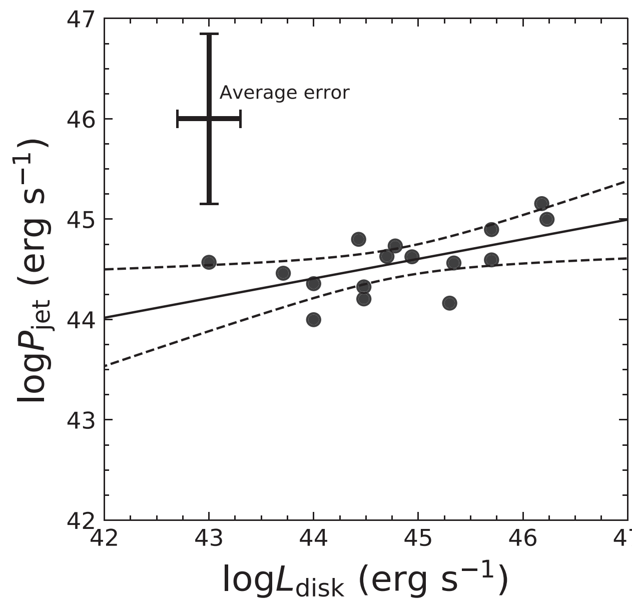

Figure 3. Relation between accretion disk luminosity and jet power. The solid lines correspond to the best-fit linear models obtained with the symmetric least-squares fit. The dashed lines indicate 2σ confidence band.

factor of is about 0.38 dex in $\log L_{\mathrm{bol}}$. The uncertainties in both $\log P_{\mathrm{jet}}$ and $\log L_{\mathrm{bol}}$ imply the large uncertainties in $\log P_{\mathrm{jet}}/L_{\mathrm{bol}}$ of about 0.93 dex. The uncertainties in both $\log M$ and $\log L_{\mathrm{bol}}$ imply the uncertainties in $\log L_{\mathrm{bol}}/L_{\mathrm{Edd}}$ of about 0.55 dex. After considering the uncertainty, these sources can be explained by the BP and/or BZ mechanism. Zhang et al. (2015) suggested that the jets of GeV NLS1s may be produced via the BP and/or BZ mechanism.

The relation between jet power and black hole mass is shown in Figure 2. The Pearson analysis shows that there is a weak correlation between jet power and black hole mass ($r = 0.46$, $P = 0.07$, significant correlation $P < 0.05$ confidence level). The Spearman correlation coefficient and significance level are $r = 0.41$ and $P = 0.11$. The Kendalltau correlation coefficient and significance level are $r = 0.28$ and $P = 0.14$. These two tests also show a weak correlation. It is generally believed that there may be a strong correlation between jet power and black hole mass. However, we find a weak correlation between jet power and black hole mass for γ-NLS1s. The possible reason is that we use small samples, and our results should be tested with large samples in the future.

Figure 3 shows the relation between jet power and accretion disk luminosity. The Pearson analysis shows that there is a significant correlation between jet power and accretion disk luminosity ($r = 0.56$, $P = 0.02$). The Spearman correlation coefficient and significance level are $r = 0.55$ and $P = 0.03$. The Kendalltau correlation coefficient and significance level are $r = 0.36$ and $P = 0.04$. These two tests also show a significant correlation between jet power and accretion disk

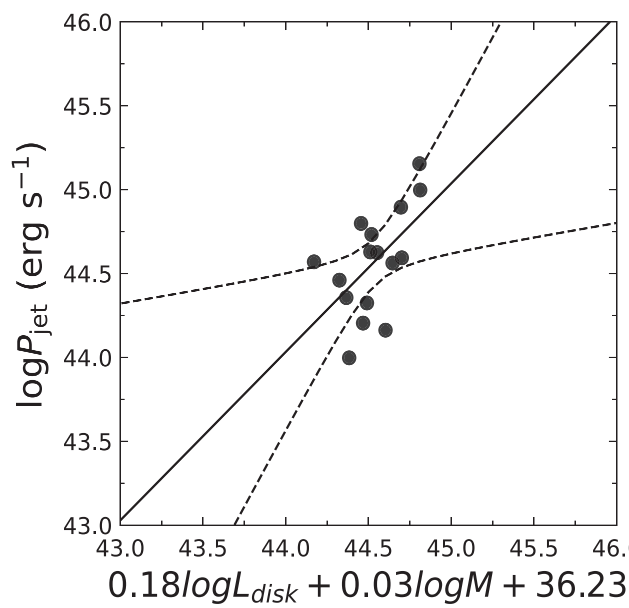

Figure 4. Relation between jet power and both accretion disk luminosity and black hole mass. The solid lines correspond to the best-fit linear models obtained with the symmetric least-squares fit. The dashed lines indicate 2σ confidence band.

luminosity. These results support a close connection between jet and accretion.

We use multiple linear regression analysis to obtain the relation between jet power and both accretion disk luminosity and black hole mass for whole sample with 99 per cent confidence level and $r = 0.57$ (Figure 4):

$$\log P_{\rm jet} = 0.18(\pm 0.12)\log L_{\rm disk} + 0.03(\pm 0.20)\log M + 36.23(\pm 4.50). \quad (12)$$

We define the contribution rates of the accretion and black hole mass to the jet power as $\xi_{\rm accretion} = 0.18/(0.18 + 0.03) \times 100\% = 85.7\%$ and $\xi_{\rm mass} = 0.03/(0.18 + 0.03) \times 100\% = 14.3\%$. The contribution rate of the accretion to jet power is larger than that of black hole mass to jet power. From the above results, we find that the jet power mainly depends on accretion, namely the BP mechanism.

5. Conclusions

We use a large sample of γ-NLS1s to study the formation mechanism of the jets. Our main results are as follows:

1. We find that the jet power of all γ-NLS1s is lower than the maximum jet power of the BP mechanism. The jet power of about 40% γ-NLS1s is lower than the maximum jet power of the BZ mechanism.
2. We find that there is a significant correlation between jet power and accretion disk luminosity. At the same time, the contribution rates of the accretion to the jet power are larger than that of black hole mass to jet power. These results further suggest that the jet of γNLS1s is mainly produced by the BP mechanism.

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